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Prepared by: Bendix Aerospace Systems Division
Prepared for: NASA/Goddard Space Flight Center

28

A.* INVESTIGATION OF TECHNIQUES FOR CORRECTING ERTS DATA FOR SOLAR AND ATMOSPHERIC EFFECTS

B. GFSC #MMC655 PR 303

Principal Investigator: Dr. Robert H. Rogers

OBJECTIVE

The objective of this experiment is to establish a radiometric calibration technique that will permit the absolute reflectance characteristics of ground targets to be determined from ERTS spacecraft data.

Intermediate Goals

The accomplishment of this objective is entailing the pursuit and accomplishment of intermediate goals that include:

- Development and evaluation of techniques to determine absolute reflectance of large natural and man-made targets from ground-based spot sampling.
- Development and evaluation of techniques to determine absolute target reflectance from ERTS data by the measurement and removal of the solar and atmospheric parameters derived from ground-based radiant power measurements.
- Inter-comparison of the capabilities of correcting the ERTS data for solar and atmospheric parameters and effects by candidate radiometric calibration techniques that include: (1) transference calibration, (2) ground-based radiant power measurements, (3) use of spacecraft data alone (no auxiliary inputs), and (4) radiation transfer models.
- Development and evaluation of computer software, techniques, and procedures for transforming the ERTS computer-compatible tapes (CCT) into a new set of tapes and images which have been corrected for solar and atmospheric effects.

*To facilitate progress review paragraph numbering (A, B, ...) is in agreement with Contract Article II, Item 2 numbering.

Scope of Work

To provide personnel and equipment necessary to develop Radiant Power Measuring Instruments (RPMI), deploy RPMIs to obtain solar and atmospheric parameters in concerts with aircraft and ERTS overflights, and to test and evaluate the procedures for using these parameters to transforming ERTC CCTs into a new set of tapes and images corrected for atmosphere. Using the performance achieved by the RPMI technique as a baseline, compare effectiveness of alternative techniques to correct ERTS data for effects of atmosphere that degrade radiometric fidelity of ERTS data.

C. There are no serious problems impeding the progress of this investigation and this program is on schedule and within budget.

D. ACCOMPLISHMENTS

Activity since 1 February has included the following:

1. Continuation of field and rooftop measurements with Radiant Power Measuring Instruments (RPMIs) to develop techniques for measuring and deriving solar and atmospheric parameters that degrade radiometric fidelity of ERTS data.

2. An ERTS tape from the 28 September 1972 overpass of test site was processed on the Bendix Ground Data System, together with RPMI measurements from 12 February 1973, to obtain a first-look evaluation of a technique for correcting ERTS CCT data for atmospheric effects.

3. This technique, which is based on the use of the RPMIs to obtain the needed solar and atmospheric parameters, was described in the paper developed and presented at the ERTS-1 Symposium on Significant Results sponsored by GSFC March 5-9, 1973. A preprint of this 8 page paper is enclosed.

4. A second paper, also enclosed and having the same title as the 8 page one, was developed to provide additional information on the RPMI and its use in obtaining the needed atmospheric parameters.

5. A 'Data Analysis Plan' was prepared and submitted on 13 March 1973. The plan was essentially unchanged from that previously provided in Section 6.0 of the original Bendix proposal BSD 1536, dated October 1971. The plan was submitted for purposes of clarifying the original proposal plan and did not change the objectives or program cost.

6. On March 27, personnel from Bendix, Cranbrook Institute, Oakland University, ERIM, and NASA participated in a joint ERTS mission within the Oakland, Wayne and Washtenaw counties area. RPMIs were deployed by three ground truth teams concurrently to measure atmospheric parameters and reflectance of test sites. Water quality measurements were also made. Primary test sites included five test lakes; (Orchard, Cass, Forest, Island, Lower Long), Barton Pond, Fighting Island (a large island in the Detroit River composed of over 63% calcium carbonate), and materials such as concrete, asphalt and grass. The NASA C-130 aircraft provided photographic and multispectral scanner coverage of these test sites from various altitudes. The aircraft also flew over large test panels of known reflectance which were deployed on the Willow Run Airport ramp.

   The RPMI atmospheric and solar measurements were taken from 07:00 hrs to 18:15 hrs. During the day the atmospheric visibility varied. Before 0900 hrs it was 15 miles but it reduced to 9 miles for the remainder of the morning and was 10 miles for most of the afternoon. The effects of this variation are seen in measurements of the atmospheric transmission. In the afternoon the atmosphere was sufficiently stable to obtain an extinction curve suitable for calculating the solar irradiance outside the atmosphere, H_o. Values of H_o differ from those measured 12 February by less than 2.5%, a value within the measurement accuracy.

   In addition to the measurement of atmospheric parameters, the RPMIs were used to measure the reflectance of test panels at Willow Run, and the reflectance of grass, concrete, asphalt and water in various locations in the 5 lakes. Upwelling radiance from the lakes was measured with the RPMI just below the water surface, just above the surface, and 3 feet above the surface.

The NASA aircraft provide coverage over the test panels and targets at altitudes that ranged from 1,600 feet to 14,000 ft. The aircraft was perfectly coordinated with the overflight of the satellite. That is, while one ground team was using an RPMI on Forest Lake the satellite and the NASA C-130 came over simultaneously. The aircraft covered all of the test sites within ± 20 minutes of the ERTS overflight.

7. Activities Planned for the Next Reporting Period

a. Complete reduction of data from the three RPMIs deployed in the 27 March mission to determine global irradiance, beam transmittance, and path radiance, and the reflectance of test sites.

b. To receive and process the ERTS CCTs from the March 27 overflight. Test sites will be located on the tapes and data within site boundaries transformed into radiance and into reflectance with the use of the RPMI derived atmospheric parameters. This reflectance will be compared with spot-reflectance measurements also made with the RPMIs in order to establish accuracy of the RPMI measurement techniques.

c. When the NASA C-130 aircraft scanner tapes are received from the 27 March mission we will also evaluate the use of this tape source to obtain reflectance of test sites.

d. I plan to make a formal request to NASA that Dr. Robert S. Fraser of GSFC be permitted to assist me. I will ask Dr. Fraser to provide computations of the solar and atmospheric parameters associated with the March 27 mission using the atmospheric models presently programmed on the GSFC computer. With this assistance by NASA, this experiment can make immediate progress toward the objective of intercomparing the capabilities of atmospheric radiation transfer models and ground-based RPMI measurements as a basis for correcting ERTS data.

e. Solar and atmospheric parameters will be continued to be measured with RPMIs for every suitable ERTS overpass of the test site. Since our rooftop location in Ann Arbor is covered two consecutive days by ERTS we will have 6 potential opportunities within the next 2 month reporting interval.

f. Studies to determine the capabilities of other techniques (such as the radiation transfer models, transfer calibration, use of spacecraft data alone) will also be continued within the next reporting period.

E. There were several significant results.

1. Although our field measurement programs have only been under way since February, we have already established that solar and atmosphere parameters degrade the radiometric fidelity of ERTS data by large amounts. The beam transmittance τ has been determined to vary more than 6.0% within a single band on a clear day. Path radiance L_{ATM} was found to account for 50% or more of the radiance signal received by ERTS when viewing water and some land masses. Global irradiance H causes the spacecraft radiance to vary up to several hundred percent depending upon spacecraft location, time, and local meteorological conditions.

2. Preliminary results indicate that RPMI will provide one technique that could be employed by a PI to obtain the needed radiometric calibration of ERTS data.

3. The March 27, 1973 mission was a significant result when the NASA C-130 aircraft and ERTS spacecraft simultaneously passed over our test sites where RPMIs were being deployed to measure solar and atmospheric parameters and site reflectance.

F. The preprint of the 8 page paper presented at the March ERTS-1 Symposium is attached, together with a more detailed (14 page) version of this paper. These two papers, together with the Data Analysis Plan, were the only documents published during this reporting interval.

G. It is recommended that NASA consider a program that would address the basic question, "what is the value of atmospheric corrections?"

To answer this question, one approach might be to select and support a group of ERTS PIs having experiments that represent a broad range of ERTS data applications, i.e., Agriculture - Crop and Soil Survey, Environmental - air and water pollution, etc., with a radiometric calibration system. This system might be composed of RPMIs or equivalent instruments that would permit the PIs to correct their data for atmospheric effects. This activity could be initiated immediately by scheduling and shipping RPMIs presently available at Bendix to select PIs. With careful scheduling and shipping of some of the 5 RPMIs, this activity would both enhance the achievement of this experiment's objectives as well as permit us to start establishing a dollar estimate of benefits contributal to atmospheric corrections.

An alternative to providing PIs RPMIs would be to provide them with both corrected and uncorrected ERTS data. The PIs would then interpret his ERTS data with and without the atmospheric corrections.

Cost of providing atmospheric corrections would be derived for each PI based on level and type of support provided. The ratio of application benefit to support cost would provide immediately the desired value (cost-effectiveness) of the atmospheric corrections for each ERTS data application.

H. A standing order change, dated 12 January 1973, requested change in size and location of test site, coverage intervals, cloud cover, and bulk black and white data products.

I. No image descriptor forms have been submitted because of recent availability of RPMIs and previous excessive cloud cover. One will be submitted for 27 March mission.

J. No retrospective orders have been submitted for the test area.

K. Work to date conforms to plans and schedule.

A TECHNIQUE FOR CORRECTING ERTS DATA FOR SOLAR AND ATMOSPHERIC EFFECTS

Robert H. Rogers and Keith Peacock
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Ann Arbor, Michigan

ABSTRACT

A technique is described by which an ERTS investigator can obtain absolute target reflectances by correcting spacecraft radiance measurements for variable target irradiance, atmospheric attenuation, and atmospheric backscatter. A simple measuring instrument and the necessary atmospheric measurements are discussed, and examples demonstrate the nature and magnitude of the atmospheric corrections.

1. INTRODUCTION

Measurements of atmospheric parameters and their use to transform ERTS data to absolute target reflectances are essential if the observations and reports of a large number of PIs are to be correlated and compared by NASA and other PIs in a meaningful way. ERTS-1 Experiment PR303 is evaluating the techniques for determining and removing solar and atmospheric effects that degrade the radiometric fidelity of ERTS data. This paper describes one technique, use of a Radiant Power Measuring Instrument (RPMI) to determine target irradiance, H, atmospheric transmittance for one air mass, τ, and the sky radiance seen by the spacecraft, L_{ATM}. Techniques for determining these parameters and the result of their use in transforming ERTS data to target reflectance is reported.

The total radiance, L, recorded by ERTS from a target of reflectivity, ρ, is related to these parameters by:

$$L = \frac{\rho H \tau}{\pi} + L_{ATM} \quad (1)$$

for a spacecraft looking vertically.

The target irradiance H can be further subdivided into:

$$H = H_o \tau^m \cos\theta + H_{sky} \quad (2)$$

where H_o is the solar irradiance outside the atmosphere, m is the atmospheric air mass in terms of the air mass at the zenith, θ is the solar zenith angle and H_{sky} is the sky irradiance. An Earth Resources investigator must therefore have an independent knowledge of H, τ, and L_{ATM} if he is to obtain the spectral reflectances of his target from the ERTS data.

2. RADIANT POWER MEASURING INSTRUMENT (RPMI)

The RPMI, developed specifically for this experiment and shown in Figure 1, provides an ERTS investigator with the capability of obtaining radiometric measurements needed to determine solar and atmospheric parameters that affect the ERTS radiance measurements.

The RPMI is a rugged, hand-carried instrument accurately calibrated to measure both downwelling and reflected radiance within each ERTS multispectral scanner (MSS) band. A foldover handle permits a quick change from wide-angle global or sky irradiance measurements to narrow-angle (6.0° circular) radiance measurements from sky and ground targets. These measurements yield ground truth site reflectance and permit calculation of additional parameters such as beam transmittance between spacecraft and ground, and path radiance (path reflectance).

12 range scales permit irradiance measurements from 0.001 to 300 W/M^2 and radiance measurements from 0.1 to 3×10^4 Wm^{-2} Sr^{-1}. The instrument is calibrated to 5% absolute and 2.0% relative from band to band.

3. MEASUREMENT OF ATMOSPHERIC PARAMETERS

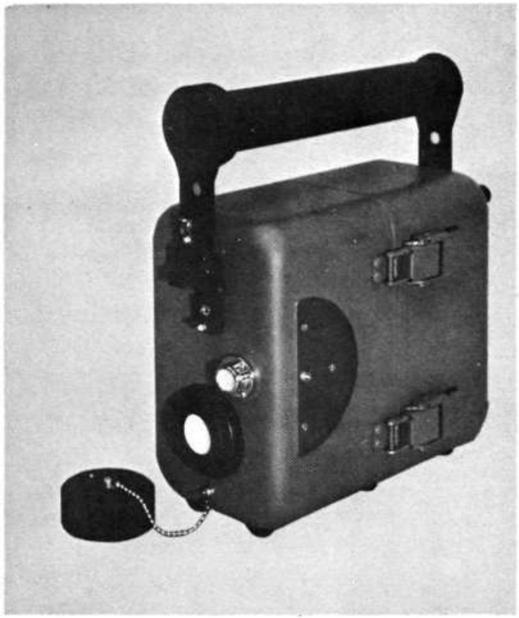
As Figure 1 shows, the RPMI is deployed in concert with ERTS overflights to obtain the direct measurements, within the four ERTS MSS bands, of: (1) global irradiance, H, (2) sky irradiance H_{sky} (i.e., by shadowing sun, and reading global minus direct beam-solar), (3) radiance from a narrow solid angle of sky $L_{meas}(\phi)$, and (4) direct beam-solar irradiance $H_{sun}(m)$. From these measurements additional solar and atmospheric parameters such as beam transmittance τ and path radiance L_{ATM} are determined, and target reflectance ρ computed using equations (1) and (2) for each spectral band.

Global Irradiance, H, is measured directly in each band as shown in Figure 1. Additional accuracy in H can be obtained by measuring the direct-beam solar irradiation, $H_{sun}(m)$ and sky irradiance, H_{sky} (direct sun shadowed out) independently and computing the total target irradiance, using:

$$H = H_{sun}(m) \cos \theta + H_{sky} \tag{3}$$

The sun angle is read from the sun dial on the side of the RPMI after leveling the instrument with its bubble level.

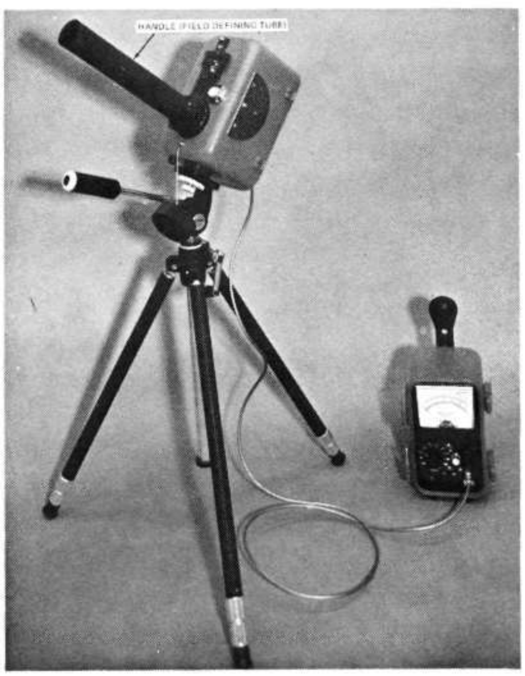
Beam Transmittance, τ, is determined by plotting an "extinction" curve, as shown in Figure 2. The direct-beam solar irradiation is plotted on a logarithmic scale as a function of the air mass. The



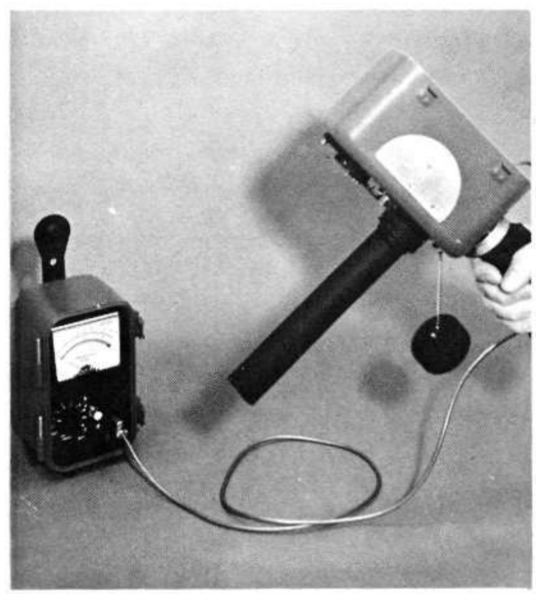
RMI Assembled

<u>Global Irradiance</u> (H) – 2π steradian field of view for measuring downwelling (incident) radiation ERTS MSS bands. Bubble level aids this measurement.

<u>Sky Irradiance</u> (H_{SKY}) – Block sun to measure global irradiance minus direct sun component, in every ERTS MSS band. Angle from zenith to sun is also measured in this mode by reading sun's shadow cast on sun dial.



<u>Radiance from Narrow Solid Angles of Sky</u> – Handle serving as field stop permits direct measurements through a 6.0° circular field of view. This mode is also used to measure direct beam irradiance.



<u>Reflected Radiation</u> – Used with small calibration panels, cards, to obtain direct measurement of truth site reflectance. Reflectance also immediately derived from ratio of reflected radiance and global irradiance.

Figure 1 Radiant Power Measuring Instrument

intercepts of the lines on the vertical axis give the solar irradiance, H_0, outside the atmosphere in each of the ERTS MSS bands, and the beam transmittance can be computed from the slope of the lines using the equation in Figure 2. Measurement of H_0 can also be used for recalibration of the instrument, without the use of additional equipment, at any location in the world.

If H_0 is known from prior observations, τ could be determined by making a single-point measurement of $H_{sun}(m)$. A correction can be made for the different zenith angles of the sun and spacecraft. This beam transmittance calculation assumes that the atmospheric properties in sun-to-target path are the same as in target-to-spacecraft path. Tests are being performed to determine the accuracy of this single-point measurement technique.

Path Radiance, L_{ATM}, is the energy reaching the spacecraft from Rayleigh and aerosol scattering by the atmosphere. As it cannot be measured directly, it must be derived from ground-based measurements of the backscatter. The simplest technique is to use RPMI to measure the sky radiance $L_{meas}(\phi)$ scattered at an angle, ϕ (as in Figure 3B) such that ϕ is identical to ϕ', the angle through which radiation is scattered to the spacecraft and correct the measurement for the difference in air masses between the direction of observation and the direction of the spacecraft. As this technique can only be used when $\theta > 45°$, atmospheric modeling is being performed to extrapolate from the available measurement angles to the desired angle.

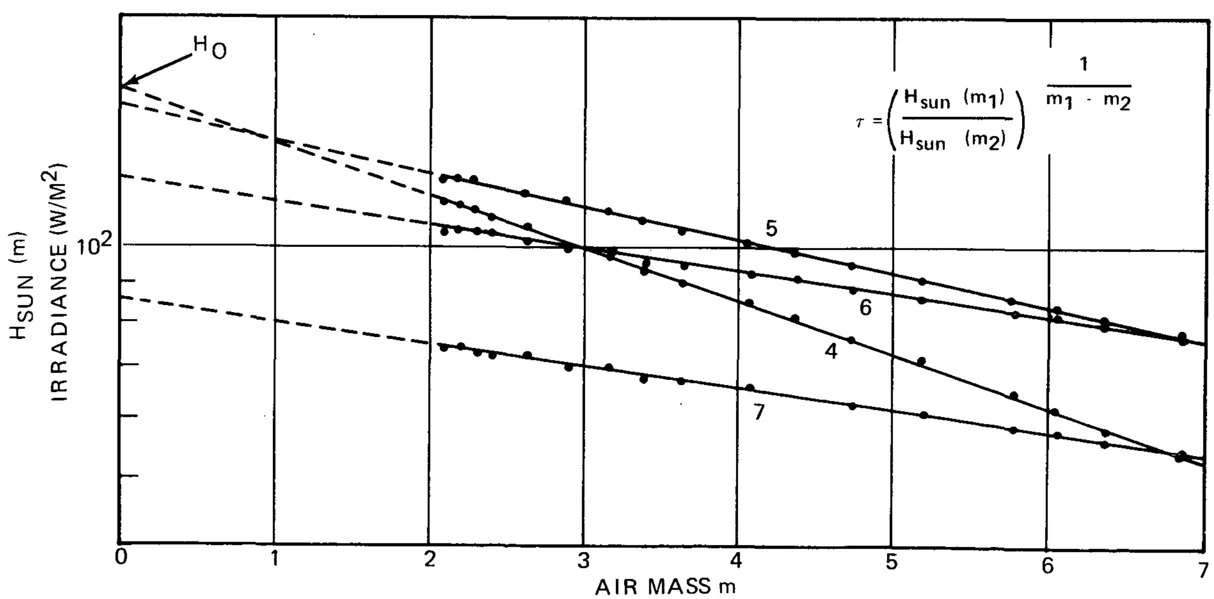


Figure 2 Atmospheric Extinction Curves

Figure 3A shows RPMI sky radiance measurements as a function of scattering angle ϕ and air mass. Each of the solid lines was obtained by pointing the RPMI at the sun and then sweeping it in azimuth, taking readings at 20° intervals for a particular elevation angle. The broken line was produced by taking readings at different elevation angles from the sun for zero azimuth. The scattering angle, ϕ, is found from:

$$\cos \phi = \sin \theta \sin \beta \cos \alpha + \cos \theta \cos \beta \qquad (4)$$

in which θ is the solar zenith angle, β is the zenith angle of the observation, and α is the azimuth measured from the sun. The air masses given in Figure 3A are the values in the direction of the observation. The air mass is continuously variable along the broken curve.

The atmospheric scattering along the line of sight should be proportional to $(1 - \tau^m)$ in which τ is the atmospheric transmission for one air mass and τ^m is the transmission of air mass m. Thus, if the RPMI radiance measurement L_{meas} is taken at a scattering angle equal to the scattering angle to the ERTS, the path radiance seen by ERTS should be related by:

$$L_{ATM} = L_{meas} \left[\frac{1 - \tau}{1 - \tau^m}\right] \qquad (5)$$

assuming the spacecraft is looking vertically through one air mass. This formula has been used by S.Q. Duntley, C.F. Edgerton, and others.

The validity of this formula was checked by multiplying the data in Figure 3A by the term containing τ in equation (5), using a value of τ determined from its extinction curve. The results are shown in Figure 3B. The radiance variation at any angle is only ±5%, which is within the measurement errors. These results can be used to give the atmospheric radiance seen by ERTS by selecting the correct scattering angle. These observations are continuing in order to determine the repeatability of the curves and the accuracy if measurements at only one or two angles are used to determine L_{ATM}.

4. EXAMPLE OF ERTS DATA CORRECTION

Since the completion of the RPMIs, local weather conditions have prevented atmospheric observations on the day of an ERTS overpass. Thus, the following comparison of atmospheric data from 12 Feb 1973 with ERTS data from 28 Sept 1972 is only to demonstrate the magnitude of the corrections and is not intended to be an accurate analysis.

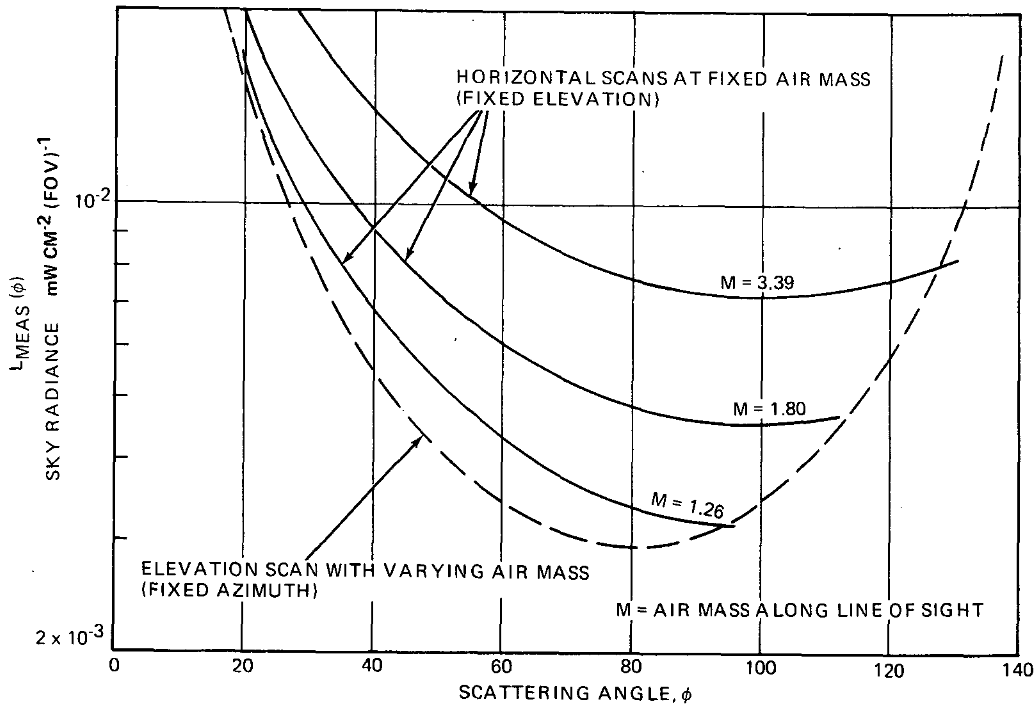


Figure 3A Atmospheric Radiance: Band 4

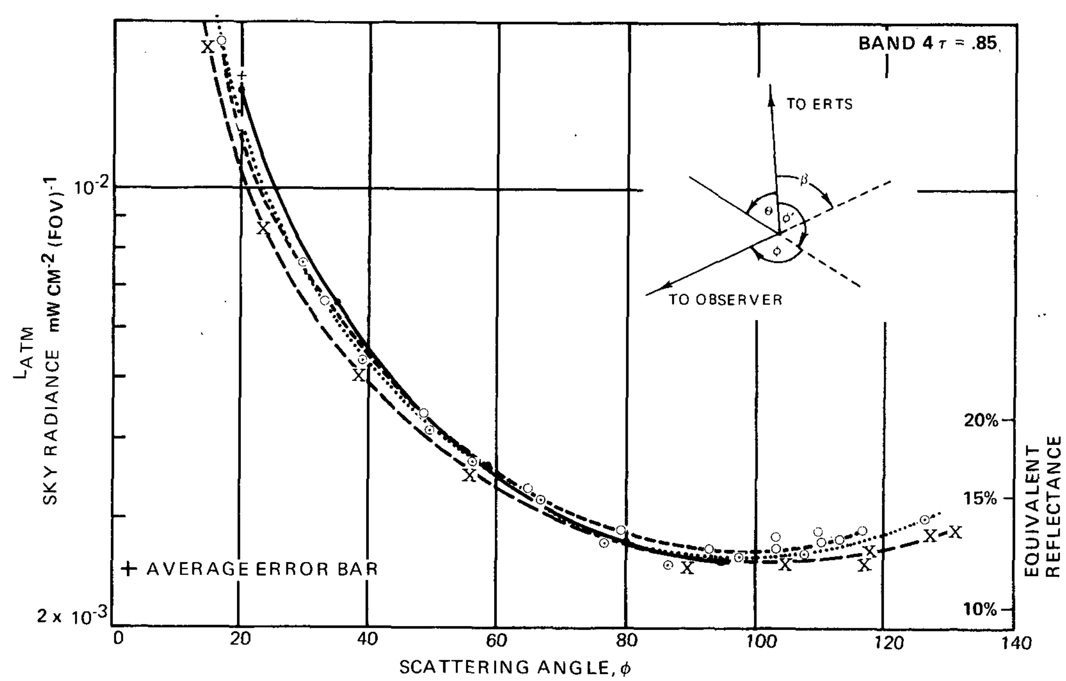


Figure 3B Scattering Data Corrected for Air Mass

Values of ERTS atmospheric path radiance were derived from data taken at Bendix in Ann Arbor, Michigan on 12 Feb 1973. Using the procedure described above, the RPMI sky radiance measurements, L_{meas}, were corrected to one air mass, and the corrected values in each of the four ERTS MSS bands were plotted as a function of the scattering angle. For a scattering angle of 131° (solar zenith angle 49°) to the ERTS, the values of L_{ATM} computed for bands 4 to 7 are listed in Table 1. These have also been converted to bit equivalents based on 7-bit levels for bands 4, 5, and 6, and a 6-bit level for band 7. The table also lists the atmospheric path radiance signal as a percentage of the full scale ERTS channel reading.

Listed in the last two columns of Table 1 are radiance values taken from ERTS data for 28 Sept 1972. The first is for water and the second is a low-lying area near the Huron River in Ann Arbor. For water, it is noted from the table that over 50% of the signal received by the spacecraft is atmospheric path radiance.

Table 2 summarizes the additional data necessary for the calculations of target reflectances. The values of H_o and τ are derived from the extinction curve as described in Section 3 using data from 12 Feb 1973. The global irradiance H is derived from the previous equation 2 using a typical measured value of sky irradiance H_{sky}. Finally, the data were used to calculate the reflectance of the target using equation (1). The results are now absolute values and are free of atmospheric and solar effects. Examples of two different targets, a small lake and a low-lying river bank, are given in Table 2.

Table 1 Atmospheric Radiance Values

Band	L_{ATM} (mW/cm^2-sr)	Bit Equivalent	% Full Scale	ERTS Data (mW/cm^2-sr) Barton Pond	Bank of River
4	0.274	14	11	0.476	0.508
5	0.118	7.5	5.9	0.242	0.276
6	0.082	6	4.7	0.141	0.402
7	0.1062	1.5	2.4	0.234	1.10

Table 2 Calculation of Target Reflectivity

Band	H_o (mW/cm^2)	τ	Global Irradiance (mW/cm^2)	Target Reflectivity	
				Barton Pond (%)	River Bank (%)
4	15.05	0.81	8.41	9.3	10.8
5	13.98	0.865	8.14	5.5	7.5
6	12.00	0.909	7.38	2.8	15
7	8.57	0.913	5.02	0.9	6.8

5. SUMMARY

Solar and atmospheric parameters degrade the radiometric fidelity of ERTS data by large amounts. Without direct measurements, the unknown atmospheric transmission, target irradiance, and sky radiance prevent the measurement of absolute target reflectance. Preliminary results indicate that the RPMI will provide a straightforward, low-cost procedure that could be employed by all PIs to obtain the needed radiometric calibration of ERTS data, thus making accurate, unambiguous interpretations possible. The ERTS-1 experiment will determine the best procedures and techniques using RPMI to obtain the needed solar and atmospheric parameters, and will utilize the performance achieved by RPMI as a baseline to evaluate alternative calibration techniques.

It is hoped that the results of this investigation will support NASA in its continuing effort to identify and bring together the most cost-effective grouping of instruments and techniques to achieve radiometric calibration of ERTS data gathered on a world-wide basis.

A TECHNIQUE FOR CORRECTING ERTS DATA FOR SOLAR AND ATMOSPHERIC EFFECTS*

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ABSTRACT

A technique is described by which an ERTS investigator can obtain absolute target reflectances by correcting spacecraft radiance measurements for variable target irradiance, atmospheric attenuation, and atmospheric backscatter. A simple measuring instrument and the necessary atmospheric measurements are discussed. Examples are given which demonstrate the nature and magnitude of the atmospheric corrections.

1. NEED

Target reflectance data are required for unambiguous interpretation of ERTS data. The capability to measure and record atmospheric parameters, and to use these parameters to transform ERTS data to absolute target reflectance signatures, is essential if the observations and reports of large numbers of PIs are to be correlated and compared by NASA and other PIs in a meaningful way. Transforming ERTS data to reflectance units also permit PIs who have knowledge of, and have compiled catalogs of, spectral reflectance of targets pertinent to their studies to extend the use of this information to ERTS imagery. Suppressing spectral variations due to atmosphere also improves computer interpretation techniques by permitting a reduction in the number of training sites needed to achieve a given level of classification performance. In summary, target reflectance data are required by all—man and machine—to maximize the usefulness of ERTS data.

2. PROBLEM

The desired reflectance information is difficult to obtain directly from the ERTS sensor radiance measurements, because these measurements are a function of unknown solar and atmospheric parameters caused by the intervening atmosphere, and these parameters vary significantly. The radiance L, sensed by the spacecraft sensor from a given target, depends not only upon the reflectance, ρ, of the target, but also upon the target irradiance, H, and upon the spectral absorption and scattering

*The results reported were accomplished during the period from August 1972 through February 1973 under NASA Contract No. NAS 5-2186.

of the atmosphere between the target and the spacecraft. This atmosphere attenuates the radiance reflected from the target to the spacecraft and adds to the foreground radiance by backscatter of sunlight from the atmosphere, L_{ATM}. The composite radiance, L, recorded within an ERTS band for a spacecraft looking vertically is therefore related to the desired target reflectance ρ and to the solar and atmospheric parameters, H, τ, L_{ATM}, by:

$$L = \frac{\rho}{\pi} H \tau + L_{ATM} \qquad (2.1)$$

where τ is the beam transmittance for one air mass. The irradiance, H, falling on the target can be expressed as:

$$H = H_o \tau^m \cos \theta + H_{sky} \qquad (2.2)$$

where H_o is the solar irradiance outside the atmosphere, m is the atmospheric air mass in terms of the air mass of the zenith, θ is the solar zenith angle, and H_{sky} is the sky irradiance. L_{ATM} will also have a dependence on θ.

It has been confirmed under ERTS-1 investigation (PR303) that even under the best possible atmospheric conditions, this radiance, L, signal will vary up to 300% even when identical test sites are viewed either repetitively or along a single orbit path. This variation in radiance is due to the contributions and variation of the unknown solar and atmospheric parameters (H, τ, L_{atm}). Thus, the Earth Resources PI who is only interested in his target characteristics, ρ, as a function of wavelength, must also have an independent knowledge of the solar and atmospheric parameters in order to uniquely determine his target reflectance. Without the knowledge of these parameters, the investigator can only interpret his ERTS data based on target spatial features and relative spectral measurements.

3. ERTS-1 ATMOSPHERIC EXPERIMENT PR303

In response to the need for absolute target reflectance signatures, the ERTS-1 Experiment PR303 is evaluating the capabilities of a wide range of candidate techniques for determining and removing solar and atmospheric parameters and effects from ERTS data. Techniques being evaluated include: (1) transferring known ground reflectance to spacecraft measurements, (2) use of the ground-based Radiant Power

Measuring Instrument (RPMI) to measure directly the needed solar and atmospheric parameters, (3) use of spacecraft data alone (no auxiliary inputs), and (4) radiation transfer models employing inputs such as surface pressure, ground visibility, temperature, relative humidity, etc.

This paper describes the results achieved to date in development of the ERTS radiometric calibration techniques employing the RPMI. Section 3 describes the instrument, and in Section 4, the procedures for deploying RPMI to obtain the required solar and atmospheric parameter (H, τ, L_{ATM}) are discussed. In Section 5, the results of using these parameters to transform ERTS radiance into the desired target reflectance is considered.

4. RADIANT POWER MEASURING INSTRUMENT (RPMI)

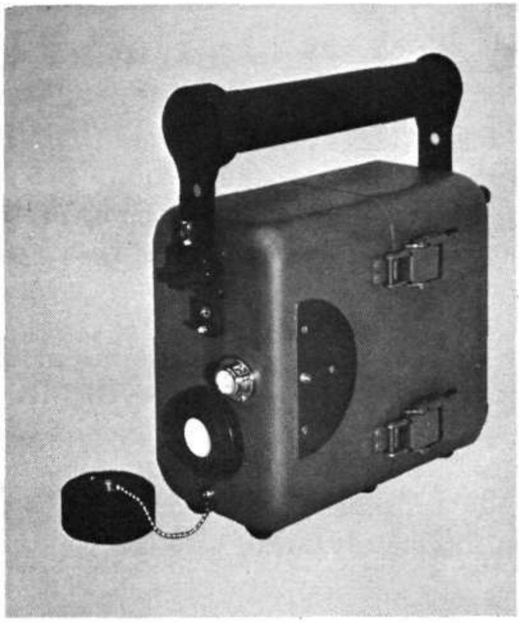
The RPMI, shown in Figure 1, provides an ERTS investigator with the capability of obtaining radiometric measurements needed to determine solar and atmospheric parameters that affect the ERTS radiance measurements. With these parameters, ERTS data are transformed into absolute target reflectance signatures, making accurate, unambiguous interpretations possible.

The RPMI is a rugged, hand-carried instrument accurately calibrated to measure both downwelling and reflected radiance within each ERTS multispectral scanner (MSS) band. A foldover handle permits a quick change from wide-angle global or sky irradiance measurements to narrow-angle radiance measurements from sky and ground targets. These measurements yield ground truth site reflectance and permit calculation of additional parameters such as beam transmittance between spacecraft and ground, and path radiance (path reflectance).

Summary of Characteristics

- Spectral Bands - All measurements made in ERTS MSS bands (0.5 to 0.6 micron (μ); 0.6 to 0.7 μ; 0.7 to 0.8 μ; and 0.8 to 1.1 μ). Bands formed by bandpass filter in switched turret followed by silicon detector.

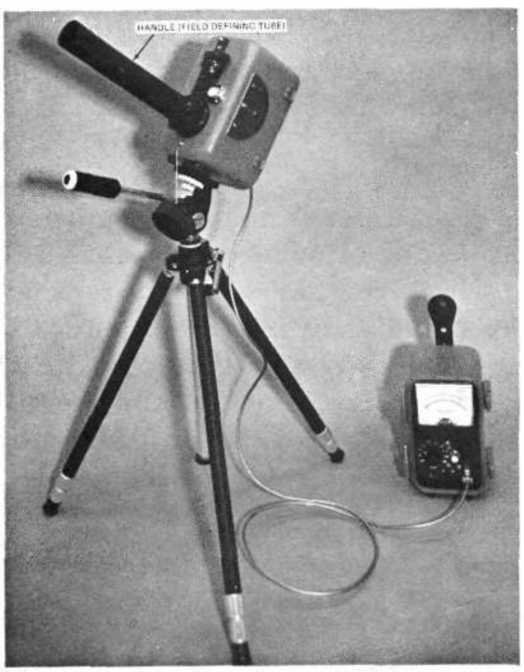
- Field of View - Two modes: (1) 2π steradian field of view through diffuser; (2) handle permits 6.0° circular field of view for sky and earth measurements.



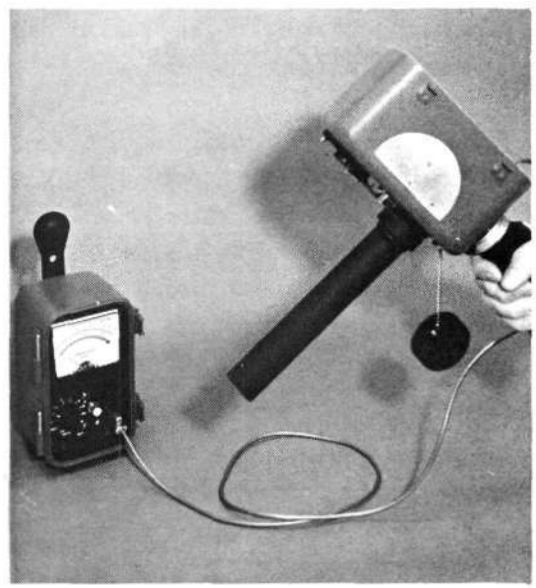
RPMI Assembled

Global Irradiance (H) – 2π steradian field of view for measuring downwelling (incident) radiation ERTS MSS bands. Bubble level aids this measurement.

Sky Irradiance (H_{SKY}) – Block sun to measure global irradiance minus direct sun component, in every ERTS MSS band. Angle from zenith to sun is also measured in this mode by reading sun's shadow cast on sun dial.



Radiance from Narrow Solid Angles of Sky – Handle serving as field stop permits direct measurements through a 6.0° circular field of view. This mode is also used to measure direct beam irradiance.



Reflected Radiation – Used with small calibration panels, cards, to obtain direct measurement of truth site reflectance. Reflectance also immediately derived from ratio of reflected radiance and global irradiance.

Figure 1 Radiant Power Measuring Instrument

- Sensitivity (measurement ranges) - 12 range scales permit irradiance measurements from 0.001 to 300 watts/meter^2 and radiance measurements from 0.1 to 3 x 10^4 watts/(meter^2 · steradian).

- Calibration Accuracy - (1) An absolute accuracy of ±5.0% is maintained over the field operating ranges for a period of over 1 year; (2) Relative (band to band) accuracy is ±2.0%; (3) Repeatability ±0.5%.

- Frequency Response - (1) 0 to 1.0 Hz on meter; (2) 0 to 20 Hz at BNC output.

- Controls - Irradiance/Radiance, Range (12 positions), Band Select (6 positions include the 4 ERTS MSS bands, and a closed and an open position), Meter Zero, Battery Test, and ON/OFF Switch.

- Meter - 3 1/2-inch taut band 1.0% hand-calibrated, mirrored scale; scaled 0 to 1.0 and 0 to 3.0 with 50 and 60 divisions, respectively.

- Power Source - 9.0-volt batteries; battery life while operating — 50 to 100 hours.

- Environmental Specifications - (1) Sealed against dust and humidity to 100%; (2) Shock and vibration expected in field and aircraft environments; (3) Storage -55°C to +80°C; (4) Operational -20°C to +70°C.

- Size - 4 x 7 x 8 in. (10 x 18 x 20 cm).

- Weight - 5.8 pounds (2.6 kg) with batteries.

4.1 Measurement of Atmospheric Parameters

As Figure 1 shows, the RPMI is deployed in concert with ERTS overflights to obtain the direct measurements, within the four ERTS MSS bands, of: (1) global irradiance, H, (2) sky irradiance H_{sky} (i.e., by shadowing sun, and reading global minus direct beam-solar), (3) radiance from a narrow solid angle of sky L_{meas} (ϕ), and (4) direct beam-solar irradiance H_{sun} (m). From these measurements additional solar and atmospheric parameters such as beam transmittance τ and path radiance L_{ATM} are determined. With these parameters the target reflectance is computed by:

$$\rho = \frac{\pi}{H\tau} (L - L_{ATM}) \qquad (4.1)$$

for each ERTS band, in terms of spacecraft radiance measurements, L, and the solar and atmospheric parameters H, τ, and L_{ATM}. The remainder of this section discusses techniques being evaluated to determine these parameters and employ them to transform the ERTS data into the desired absolute target reflectance characteristics.

Global Irradiance H - The radiation falling on the target is measured directly in each ERTS MSS band, as shown in Figure 1. Since this instrument employs a roughened flashed opal disc for a diffuser to obtain this 2π steradian measurement, and diffusers of any type introduce some error as a function of sun angle, additional accuracy in H may be obtained by measuring direct beam solar irradiance H_{sun} (m), sun zenith angle θ, and sky irradiance H_{sky}. These parameters are then simply combined by:

$$H = H_{sun}(m) \cos\theta + H_{sky} \tag{4.2}$$

H_{sun} is a direct meter reading when RPMI is pointed at the sun as in Figure 1. Sky irradiance is also a direct meter reading when the instrument is mounted horizontally, as shown in Figure 1 and the direct-beam sun component is blocked (shadowed out). Sun angle measured from the zenith is also read directly from the sun dial in this mode. Additional accuracy may be obtained if desired by computing sun angle.

Beam Transmittance, τ - One method for determining the beam transmittance τ is to use the RPMI to obtain an "extinction" curve. This technique, widely used by astronomers, follows:

- Measure the direct beam solar irradiation H_{sun} (m) for a range of solar zenith angles. This is a direct meter reading when the RPMI is pointing at the sun as in Figure 1.

- For each measurement, calculate air mass $m = \sec\theta$.

  For sun angles greater than 70°, a more accurate value of m is given by the equation: $m = \sec\theta - 0.0018167 (\sec\theta - 1) - 0.002875 (\sec\theta - 1)^2 - 0.0008083 (\sec\theta - 1)^3$, the sun zenith angle θ being read directly from the sun dial or calculated.

- Plot log H_{sun} (m) against m and extrapolate to m = 0 to read H_o, as shown in the example of Figure 2.

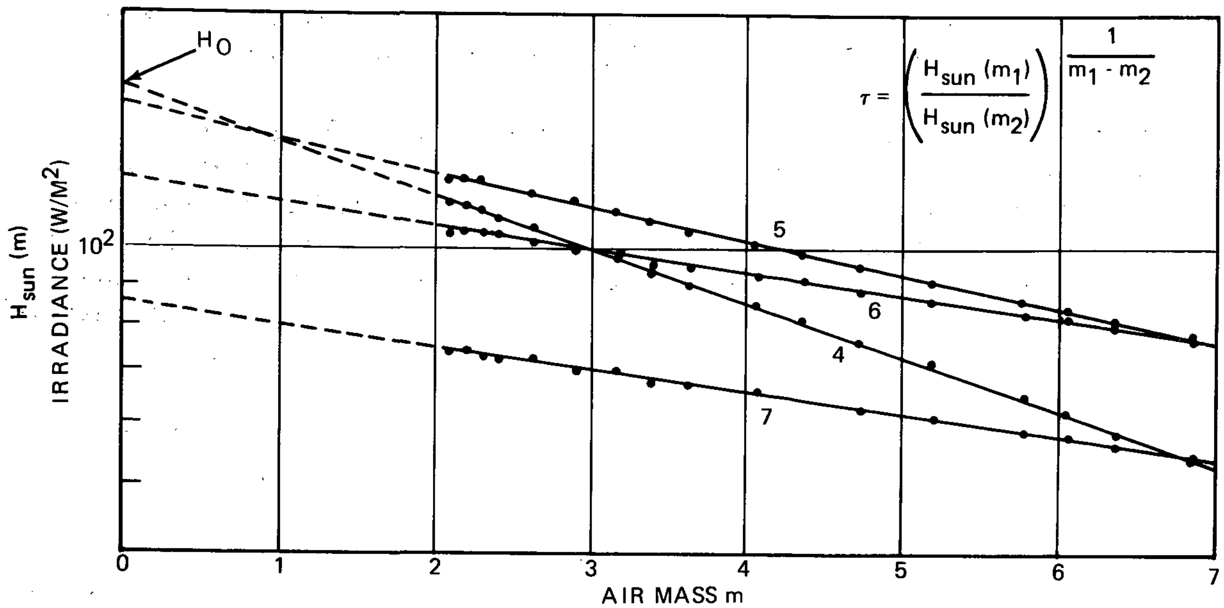


Figure 2 Atmospheric Extinction Curves

The straight lines in Figure 2 indicate excellent, stable atmospheric conditions. The intercept of the lines on the vertical axis give the solar irradiance H_o outside the atmosphere in each of the four MSS bands. The slopes of the lines give the atmospheric attenuation τ, which, as expected, increases with decreasing wavelength. The measured values of H_o can be compared with known values and used as a direct calibration of the instrument. This powerful calibration technique permits recalibration of the RPMI on a clear day at any place in the world without the use of additional equipment or complicated computation procedures.

The parameter τ is determined for each ERTS band in terms of fractional absorption per air mass by obtaining the slope of the curves in Figure 2, which is simply:

$$\tau = \left(\frac{H_{sun}(m_1)}{H_{sun}(m_2)}\right)^{\frac{1}{m_1 - m_2}} \tag{4.3}$$

where:

$H_{sun}(m_1)$ = direct beam solar irradiance at air mass m_1.
$H_{sun}(m_2)$ = direct beam solar irradiance at another air mass m_2.

The atmosphere properties along the spacecraft-to-target path are assumed to be the same as along the instrument-to-sun path.

A disadvantage of this method is the necessity of making a series of measurements over several hours to obtain a range of sun angles. However, if a single good extinction curve is obtained on a clear day with each instrument, the instruments can be calibrated directly against the sun. Future measurements at a single zenith angle, such as one when ERTS passes over the test site, can then be used to find the atmospheric transmission τ.

In this case, the atmospheric transmission, τ (θ) along the sun-to-instrument path, will be given by:

$$\tau\ (\theta) = \frac{H_{sun}\ (m)}{H_o} \tag{4.4}$$

The sun-target transmittance is used to calculate the target-spacecraft τ (S) transmittance, using:

$$\tau\ (S) = \tau\ (\theta)^{\frac{\cos\theta}{\cos S}} \tag{4.5}$$

where S is the spacecraft angle of observation. For most cases, S $S \simeq o$, so:

$$\tau\ (S) = \tau\ (\theta)^{\cos\theta} \tag{4.6}$$

A series of tests is being performed for ERTS-1 to determine the accuracy of such a single point measurement.

Path Radiance, L_{ATM} - The signal detected by the ERTS will have a minimum value for each band which corresponds to the atmospheric radiance. This radiance is caused by Rayleigh and aerosol scattering. As it cannot be measured directly, it must be derived from ground-based measurements of the backscatter.

The simplest technique is to use RPMI to measure the sky radiance L_{meas} (ϕ) scattered at an angle, ϕ as in Figure 3 such that ϕ is identical to ϕ' the angle through which radiation is scattered to the spacecraft and correct the measurement for the difference in air masses between the

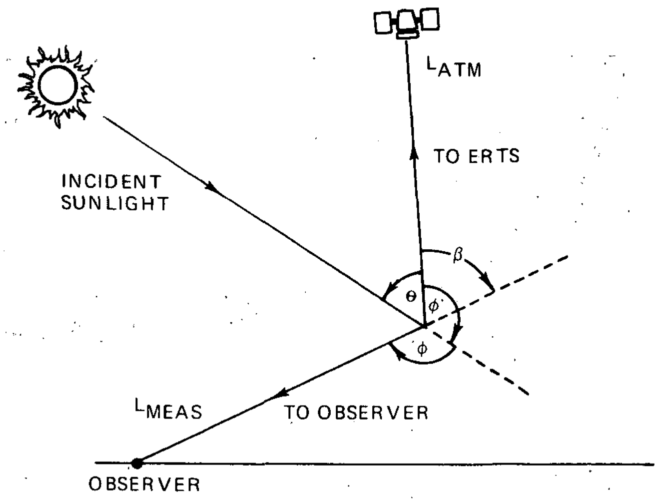


Figure 3 Angular Relationship

direction of observation and the direction of the spacecraft. It is apparent that this RPMI measurement can be made only when the sun zenith angle $\theta > 45°$, which, in some cases, is an unacceptable restriction on the measurements. Atmospheric modeling must be used to extrapolate from the available angles to the desired angle as well as to check the dependence on air mass. A series of measurements is being performed by Bendix to permit an accurate interpolation with a minimum of measurements.

Figure 4A shows RPMI sky radiance measurements as a function of scattering angle ϕ and air mass. Each of the solid lines was obtained by pointing the RPMI at the sun and then sweeping it in azimuth, taking readings at 20° intervals for a particular elevation angle. The broken line was produced by taking readings at different elevation angles from the sun for zero azimuth. The scattering angle, ϕ, is found from:

$$\cos \phi = \sin \theta \sin \beta \cos \alpha + \cos \theta \cos \beta \qquad (4.7)$$

in which θ is the solar zenith angle, β is the zenith angle of the observation, and α is the azimuth measured from the sun. The air masses given in Figure 4A are the values in the direction of the observation. The air mass is continuously variable along the broken curve.

The atmospheric scattering along the line of sight should be proportional to $(1 - \tau^m)$ in which τ is the atmospheric transmission for one air mass

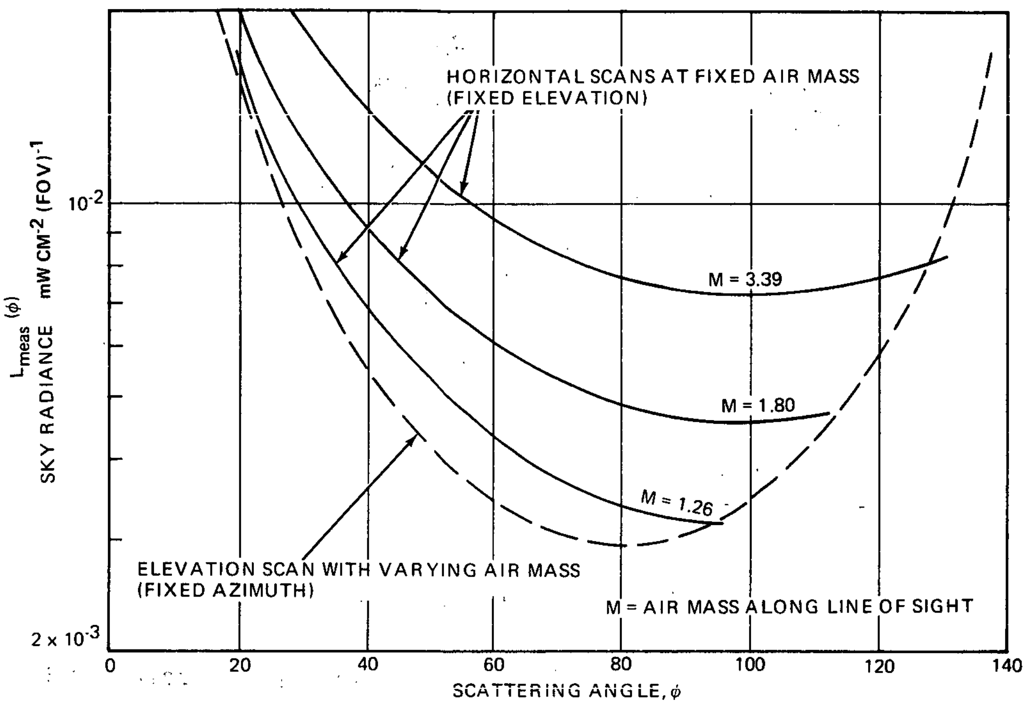


Figure 4A Atmospheric Radiance: Band 4

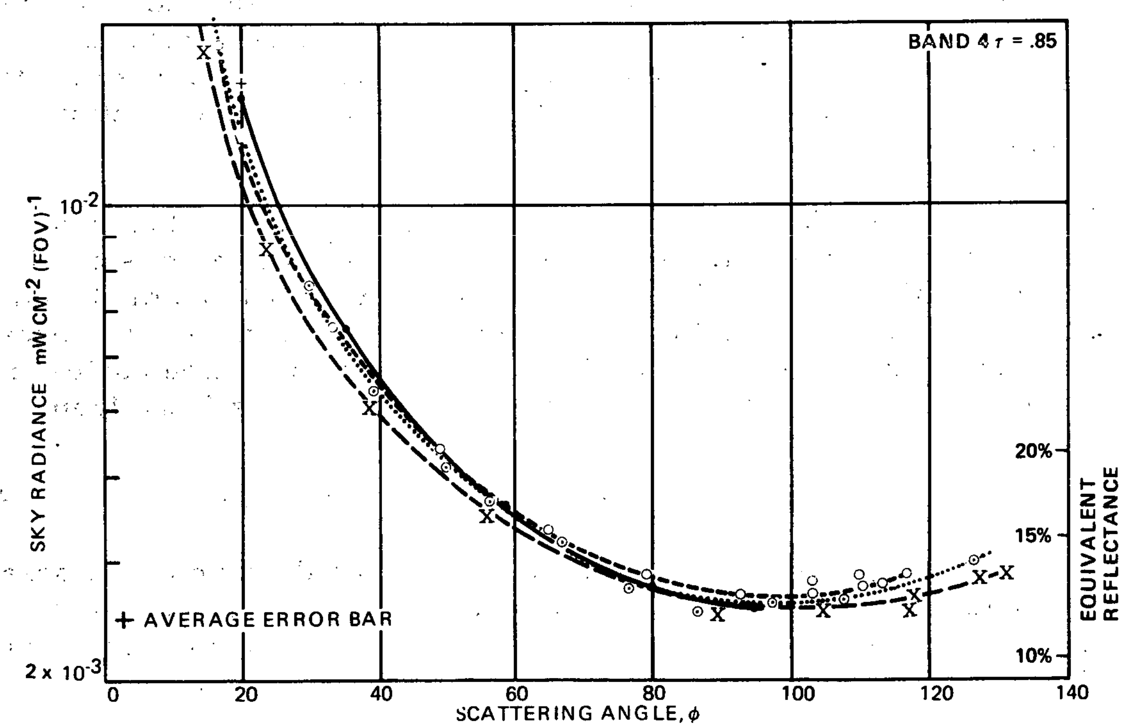


Figure 4B Scattering Data Corrected for Air Mass and τ^m is the transmission of air mass m. Thus, if the RPMI radiance measurement L_{meas} is taken at a scattering angle equal to the scattering angle to the ERTS, the path radiance seen by ERTS should be related by:

$$L_{ATM} = L_{meas} \left[\frac{1 - \tau}{1 - \tau^m}\right] \qquad (4.8)$$

assuming the spacecraft is looking vertically through one air mass. This formula has been used by S.Q. Duntley, C.F. Edgerton, and others.

To check the validity of the formula, each of the results in Figure 4A was multiplied by the term in equation 4.8, the value of τ having been determined from an extinction curve. When the curves are replotted, the angular distribution has the form shown in Figure 4B. Considering that the RPMI angular pointing accuracy was only $\pm 1°$ for this test and the atmospheric conditions were unsettled (clearing of a slight haze caused τ to increase from 0.80 to 0.85 in 3-4 hours), the agreement of the curves is excellent. The angular distribution is consistent and the radiance variation at any point is only $\pm 5\%$, or considerably less if the least accurate curve, the lower one, is given less weight. Thus, for a sun angle of 60° the sky radiance seen by ERTS is given by the value at a scattering angle of 120° (i.e., 180° $- \theta$).

These observations are continuing to determine the repeatability of the curves and the accuracy if measurements at only one or two angles are used to determine L_{ATM}. It may be possible to determine the curve by making a single measurement at an angle of 90° from the sun.

5. EXAMPLE OF ERTS DATA CORRECTION

Since the completion of the RPMIs, local weather conditions have prevented atmospheric observations on the day of an ERTS overpass. Thus, the following comparison of atmospheric data from 12 Feb 1973 with ERTS data from 28 Sep 1972 is only to demonstrate the magnitude of the corrections and is not intended to be an accurate analysis.

Values of ERTS atmospheric path radiance were derived from data taken at Bendix in Ann Arbor, Michigan on 12 Feb 1973. The weather condition — average haze — caused low atmospheric transmission. Using the previously described procedure, the RPMI sky radiance measurements, L_{meas} were corrected to one air mass, and the corrected values in each of the four ERTS MSS bands were plotted as a function of the scattering angle. For a scattering angle of 131° (solar zenith angle 49°) to the ERTS, the values of L_{ATM} computed for bands 4 to 7 are listed in Table 1. These have also been converted to bit equivalents based on 7-bit levels for bands 4, 5, and 6, and a 6-bit level for band 7. The table also lists the atmospheric path radiance signal as a percentage of the full scale ERTS channel reading.

Table 1 Atmospheric Radiance Values

Band	L_{ATM} ($mW/cm^2/sr$)	Bit Equivalent	% Full Scale	ERTS Data ($mW/cm^2/sr$) Barton Pond	Bank of River
4	0.274	14	11	0.476	0.508
5	0.118	7.5	5.9	0.242	0.276
6	0.082	6	4.7	0.141	0.402
7	0.1062	1.5	2.4	0.234	1.10

Listed in the last two columns of Table 1 are radiance values taken from ERTS data for 28 Sept 1972. The first is for water and the second is a low-lying area near the Huron River in Ann Arbor. For water, it is noted from the table that over 50% of the signal received by the spacecraft is atmospheric path radiance.

Table 2 summarizes the additional data necessary for the calculations of target reflectances. The values of H_o and τ are derived from the extinction curve as described in Section 4 using data from 12 Feb 1973. The global irradiance H is derived from the previous equation 2.2 using a typical measured value of sky irradiance H_{sky}. Under normal circumstances, the direct beam solar irradiance $H_o\tau^m$ is a fast direct measurement made at the time of the ERTS flyover, but as the atmospheric data and the ERTS results were for different sun angles, equation 2.2 was used to determine the global irradiance H. The results are given in the table. Finally, the data were used to calculate the reflectance of the target using equation 4.1. The results are now absolute values and are free of atmospheric and solar effects. Examples of two different targets, a small lake and a low-lying river bank, are given in Table 2.

Table 2 Calculation of Target Reflectivity

Band	H_o (mW/cm^2)	τ	Global Irradiance (mW/cm^2)	Target Reflectivity	
				Barton Pond (%)	River Bank (%)
4	15.05	0.81	8.41	9.3	10.8
5	13.98	0.865	8.14	5.5	7.5
6	12.00	0.909	7.38	2.8	15
7	8.57	0.913	5.02	0.9	6.8

6. SUMMARY

The ERTS-1 experiment is determining the procedures and techniques for best using RPMI to obtain the needed solar and atmospheric parameters. The performance and cost of this procedure will then be used as a basis to compare other techniques for obtaining the atmospheric parameters needed to transform ERTS radiance into absolute target reflectance. Preliminary results indicate that RPMI will provide a straightforward, low-cost procedure that could be employed by all PIs to obtain the needed radiometric calibration of ERTS data, thus making accurate, unambiguous interpretations possible.

Although our field measurement programs have just started, we have established that solar and atmosphere parameters degrade the radiometric fidelity of ERTS data by large amounts. The beam transmittance τ has been determined to vary more than 6.0% within a single band on a clear day. Path radiance L_{ATM} was found to account for 50% or more of the radiance signal received by ERTS when viewing water and some land masses. This has also been confirmed by computations performed by R. S. Fraser at NASA GSFC. Global irradiance H causes the spacecraft radiance to vary up to several hundred percent depending upon spacecraft location, time, and local meteorological conditions. Under the assumption of clear sky conditions, computational techniques will provide a fair estimate (within 20 to 30%) of global irradiance. The RPMI provides the ERTS PI with a direct, absolute measurement of this parameter in each ERTS MSS band.

It is hoped that the results of this investigation will support NASA in its continuing effort to identify and bring together the most cost-effective grouping of instruments and techniques to achieve radiometric calibration of ERTS data gathered on a world-wide basis.